FAILURE MODES AND PREDICTIVE DIAGNOSTICS CONSIDERATIONS FOR DIESEL ENGINES

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Abstract: Diesel engines are well known for their operational robustness and efficient performance. These attributes make them a leading choice for prime movers in critical DoD, industrial, and mobility applications. Despite the diesel engine's known reliability, there are some operational issues that justify monitoring critical engine components and subsystems in order to increase the overall availability and readiness of diesel-powered systems. Moreover, engines typically constitute a significant fraction (1/10-1/5) of the acquisition cost and a comparable fraction of the life cycle cost for mobility applications (trucks, armored vehicles), thereby providing the motivation for engine condition monitoring on the basis of reducing life cycle costs. Review of the available literature indicates that the fuel injection and cooling subsystems are among the most problematic on diesel engines contributing to reduced readiness and increased maintenance costs. These faults can be addressed and studied using scaled testing to build the necessary knowledge base to quickly transition the methods to full-scale, more costly diesel engines.

Towards this goal, a Diesel Enhanced Mechanical Diagnostics Test Bed (DEMDTB) has been developed that uses an array of sensors to measure pressure, temperature, vibration, and displacement. The test bed is used for experimental collection of healthy, seeded fault, and transitional fault test data from the diesel engine and driveline components. The data is analyzed with time and frequency based analysis methods to characterize 'healthy' and 'faulty' operation.

The purpose of this paper is to present an overview of previous research conducted for diesel engine diagnostics, discuss recent diesel engine diagnostics developments, and to lay the basis for straightforward concept designs for practical diesel engine monitoring/diagnostics systems that will enable system prognostics.

Key Words: Condition-Based Maintenance (CBM); diesel engines; Diesel Enhanced Mechanical Diagnostics Test Bed (DEMDTB); FMEA.

Introduction: Diesel engines are widely used as generators and prime movers in industry and the military for their durability and efficient performance and they are often used in applications where reliability is a crucial operating requirement. Large and

medium size diesel engines can be found in electrical power plants as the prime movers of large oceanic vessels. Meanwhile smaller, high-speed engines have been found in tractors, trucks, cars and small marine vessels. Diesel engines are also used for a wide variety of military applications. For example, the US Navy uses diesel engines in a variety of roles in the fleet. Numbering in the thousands, applications for these engines range from main propulsion and service power generation down to fire hose pumps. These engines range in power from less than 50 hp to above 12,000 hp. Diesels are used on roughly 30 classes of ships across the Navy. Currently over 200 diesel engines that are greater than 2,000 hp are being used for main propulsion on the LSD, LST, and PC class ships [1]. The U.S. Army and Marine Corps are also heavily reliant upon diesel engines as prime movers where the majority of combat and transport vehicles in use (with the exception of main battle tanks) are powered by diesel engines. The Advanced Amphibious Assault Vehicle, currently in the acquisition process, uses a high-powered, MTU diesel engine. Some of these systems have a good deal of performance monitoring and limited diagnostics. However, the authors have seen no commercial system with true prognostic capability.

Considering the manning reduction issues that the military and many industries are faced with coupled with the need for diesel engine maintainability, it is logical that a Condition-based Maintenance (CBM) system be developed for monitoring diesel engine operation. The justification for implementing a CBM program should be evaluated on a case-by-case basis but when diesel engine dependability is crucial to mission effectiveness, then that system is an excellent candidate for the application of a CBM program. Financially feasible applications for such advanced maintenance systems are in nuclear power plants, offshore oil rigs, hospitals, and in various remote unmanned facilities. The need for cost-efficient maintenance programs in the military is evident by the overwhelming size and age of the armed forces vehicular fleet. The average age of the U.S. military's 850,000 vehicles is twelve years, which makes maintaining operational readiness a paramount concern and also a costly expenditure of more than five billion dollars annually [2].

Operational Characteristics of Diesel Engines: Diesel engines are comparable to spark ignited (SI) engines in many respects, with the exception that they use the heat produced from the compression stroke for ignition rather than spark plugs. Diesel fuel is injected at high pressure into the cylinder after the air has been compressed to such a point where auto-ignition occurs. The compression ratio of diesel engines can be greater than twice that of SI engines, which translates into greater efficiency.

The combustion process of the diesel engine is highly dependant upon the precise injection of atomized fuel into the cylinder or swirl chamber. The fuel injection system controls the injection pressure (necessary for atomization and mixture) and dispenses a metered amount of fuel for specified speed and load conditions, and has effects upon emissions and overall engine noise. The reliable operation of the fuel injection/delivery system is thus a paramount concern for both engine manufacturers and maintenance personnel. The development of the distributor-type injection pump with automatic timing (introduced in the early 1960's) and Electronic Diesel Control (developed during the

1970's) have contributed greatly to the increased power output and lower emissions of modern engines [3].

Diesel Engine Fault Analysis: Research efforts related to the development of diesel engine diagnostic systems have typically been guided by a thorough knowledge of component failure modes. A reliability-based engineering method that is commonly employed as an evaluation tool is Failure Mode and Effects Analysis (FMEA). FMEA charts describe the function of a component, potential failure modes, possible causes of failure, and the effects such failures would have upon the system's operation. Other versions of how to capture this information are employed in RCM II analysis and FMECA (Failure Modes, Effects and Criticality Analysis). The FMEA chart shown in Figure 1 is for large, medium-speed marine diesel engines typically employed in large commercial vessels.

FMEA Chart for Fuel Oil Supply System

Component	Function	Failure Mode	Possible Cause of Failure	Effects on System
Fuel Oil Injection Pumps	provide engine with fuel in quantities corresponding to power required and timed correctly	broken delivery valve springs		poor atomization fouling misfiring of cylinders
		choked fuel valves	contaminated fuel	loss in power
		cavitation	local pressure falls below saturated vapor pressure of fuel	pump erosion
Fuel Oil Injectors	atomize fuel in combustion chamber and to ensure that it mixes with sufficient air for complete combustion in cycle time available	incorrect atomization	choked atomizer due to contaminated fuel debris and hot gas from cylinder forming carbon	incorrect combustion
		cavitation	low pressure caused by pressure waves that move between injector and fuel pump at end of fuel injection; delivery valve breakage also aggravates cavitation	injector erosion
High pressure Fuel Lines		cavitation	same as item 2	erosion in high-pressure fuel lines, ultimately resulting in rupture of main fuel line

Figure 1 - FMEA Chart of Fuel Oil Supply Systems [3]

It is also important to understand which of the failures described in the FMEA have the highest rate of occurrence during operation. Comparisons of component failure rates obtained from studies of twenty similar marine diesel engines are shown in Figure 2. This information allows diagnostic research to be tailored to address failure mechanisms that occur on a significant basis under typical operating conditions.

Failures of the fuel oil valve represent greater than 30% of the recorded failures, while twelve components account for roughly 90%. A review of other studies corroborates the

high failure rates of the fuel delivery system, cylinder head, valves and cooling system shown in Figure 2. A summarized list of fault areas obtained from the reviewed studies is shown below (listed in order of priority).

(1) Fuel Injection System
(2) Cylinder Head and Valves
(3) Charging and Exhaust System
(4) Cooling System
(5) Bearings, Pistons, Liners, Timing Gears, etc.

The reviewed information clearly indicates that the fuel injection system has been the most prevalent source of problems for diesel engines. Meanwhile, engine components subjected to high levels of wear, such as pistons, liners and bearings rank near the bottom.

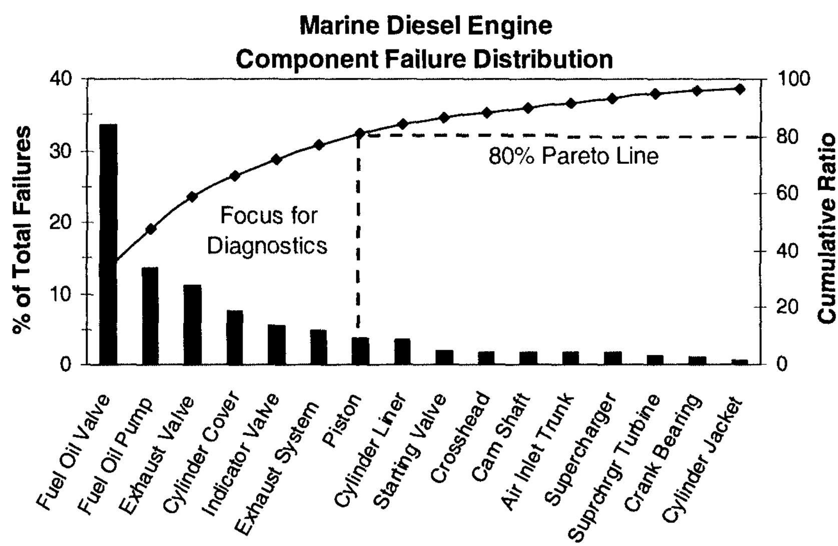


Figure 2 - Marine Diesel Engine Component Failure Distribution [4]

From the study on marine diesel engines, a comparison was made between the amount of maintenance attention given to engine components versus their corresponding failure rates. Figure 3 shows that the high failure rates of individual components described in Figure 2 are not caused by lack of proper maintenance attention. It also shows that preventative maintenance (PM) is properly distributed to those parts that are most prone to failure or are critical to engine performance.

It should be noted that due to the nature of the preventive maintenance techniques employed, it would be expected that frequent component replacements, regularly scheduled maintenance, and yearly overhauls should be reflected in these numbers as components are discarded prior to the end of their useful life. Unlike a preventative maintenance program, a CBM system would allow these components to operate

throughout their extended design life cycle. A shift might therefore be expected in fault distributions once the engine is being maintained with a CBM approach rather than by PM.

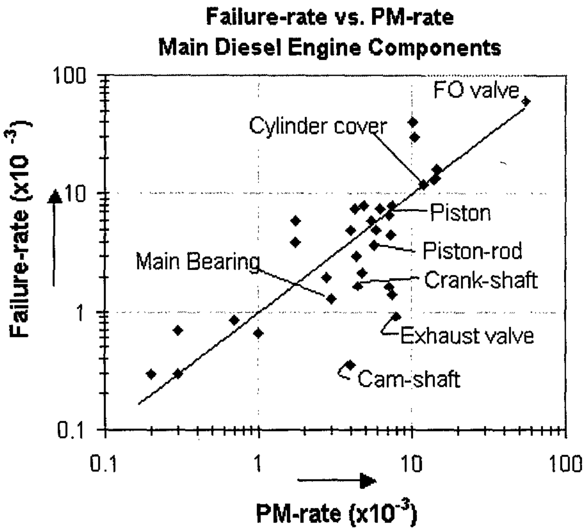


Figure 3 - Main Diesel Engine Components, Failure-rate vs. PM-rate [4]

Diesel Engine Diagnostics: Condition monitoring systems and fault diagnostics techniques have been developed to reduce maintenance costs and to increase machinery availability for critical mechanical systems. This is accomplished by comparing measured operational parameters to normal machine condition baseline levels, with the residual representing an indication of a possible fault condition. Understanding the correlation between the parameter and the components or mechanical functions that they represent provides insight into the root cause of machinery faults.

There are a number of parameters that can be measured and monitored on diesel engines including: pressure, temperature, flow rates and vibration. Currently, the most prevalent diagnostic evaluation technique is cylinder pressure analysis, which has been used extensively to monitor the engine combustion process. By evaluating deviations from pre-established, 'healthy' pressure-time curves of each of the cylinders it is possible to detect a variety of abnormal operating conditions. Peak firing pressure, peak firing pressure crank angle, maximum pressure rise rate, start of injection, and start of combustion are key reference points used in diesel engine cylinder pressure analysis [5,6].

Additionally, vibration and acoustic analysis of diesel engine operation has been increasingly employed in diagnostic systems and holds great potential for predictive diagnostics research. Spectrum analysis of engine vibration data has typically been a

subjective process in which observed patterns are compared to reference or baseline conditions in order to identify operating anomalies. Liner scuffing, blow-by and improper fuel injection are a few specific faults that have been detected by this method. The basis for acoustic (ultrasound) analysis of engine noise stems from the capability of experienced maintenance personnel to diagnose faults through observed sound qualities. This process involves using either high frequency vibration transducers (35-45kHz range) or acoustic ultrasonic detection equipment [5].

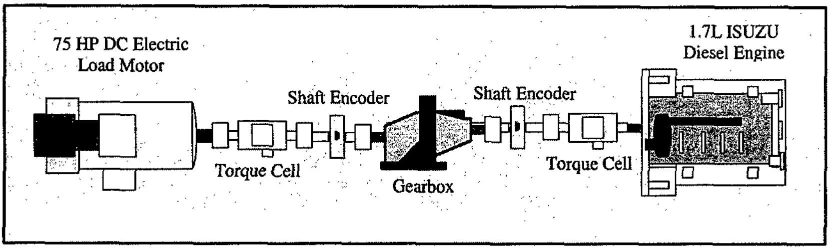
The System Material Analysis Department of the Commonwealth Edison Company illustrate a method for diagnosing diesel engine blow-by using ultrasonic and pressure analysis [7]. Blow-by is fault condition usually indicative of piston ring or cylinder wear. The most salient symptom for this condition is an increase in the vibration level that coincides with high cylinder pressures. The large vibrations occur due to the leakage of combustion gases past the piston rings.

Condition monitoring and wear debris analysis of lubricating oil are frequently used to complement data obtained from the cylinder pressure analysis. Assessing the health of lubrication oil is especially important for industrial and marine applications of large and medium size diesel engines. Lubricant contamination occurs primarily in the form of metallic debris produced from the mechanical wear of engine components and from leakages into the system. Various methods of wear debris analysis, typically involving forms of spectroscopy or ferrography, offer valuable insight into component wear rates and thus provide a means to detect rapidly deteriorating engine components prior to failure. Spectroscopy assesses the elemental content of oil by measuring the frequency and intensity of light emitted from electrically excited particles, whereas ferrography entails the separation of ferromagnetic fluid particles from the lubricant through contact with a magnetic field [8].

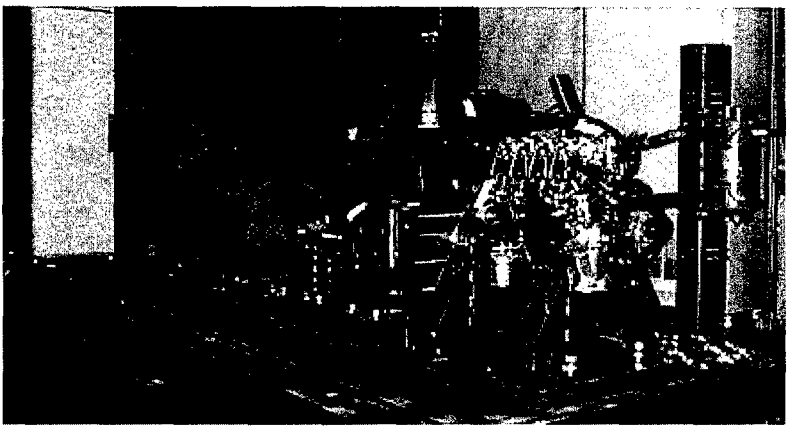
Diesel Enhanced Mechanical Diagnostic Test Bed (DEMDTB): A test cell for performing transitional and seeded fault research on a reciprocating engine and mechanical drive train parts is a key enabler towards the development of diagnostic and prognostic capability. The Diesel Enhanced Mechanical Diagnostic Test Bed (DEMDTB) system is capable of generating diesel engine operational data at the component and subsystem level under variable speed and load conditions. It provides the opportunity for conventional and advanced sensing techniques on real machinery in a controlled environment.

The DEMDTB provides two methods of driving forces for testing: electric motor or diesel engine. A block diagram layout of the DEMDTB in the diesel engine drive configuration is shown in Figure 4. The DEMDTB provides accurate torque and speed information via torque cells and shaft encoders mounted on the drive and load shafts. Secondary torque and speed measurements are also provided from the electric motor controllers.

The 1.7-liter 4-cylinder Isuzu diesel engine shown on the test bed in Figure 4, provides a continuous output of 36.1 bhp @ 3000 rpm with a maximum rating of 80.0 ft-lbs @ 1800 rpm. This test bed provides an effective means for studying health indication parameters for a representative diesel engine. Seeded faults in the diesel engine may



(a)



(b)

Figure 4 - Schematic and Picture of Diesel Enhanced Mechanical Diagnostic Test Bed

include excessive wear on piston rings and valves or a cracked crankshaft and lifter rods. While the DEMDTB provides a new mechanism for developing diesel diagnostics, the test bed still provides a means for testing different types of gearboxes and other mechanical devices.

Data Acquisition and Control System: A C-sized, VXI rack-mount data acquisition system connected to a Pentium based rack mount computer via an IEEE-1394 fire-wire interface is implement on the DEMDTB. This rack mount system is capable of housing 13 different types of VXI boards. Currently, the system contains one Agilent E1433 and one Agilent E1437.

The Agilent E1433 digitizes 8-channels at a rate of 196,000 samples/sec with 16-bits of amplitude resolution. The module provides transducer signal conditioning, anti-alias protection, digitization and measurement computation. The onboard digital signal processor and 32 Mbytes of RAM maximizes total system performance and simplifies

system integration. Using separate analog-to-digital converters (ADC) for each channel, the E1433 provides simultaneous sampling across all channels. Simultaneous sampling guarantees accurate channel-to-channel comparisons, both in the time and frequency domains and is required for phase analysis and order resampling analysis. The E1433 uses sigma-delta ADCs with 64X over-sampling which allows for low-order analog anti-alias filters and permits all filtering and sample-rate conversions to be performed digitally thereby providing stable and drift-free filtering.

The Agilent E1437 digitizer provides one channel at 20Msamples/sec sample rate with an amplitude resolution of 23-bits. This module is capable of recording reliable high frequency data up to a 10MHz bandwidth for torsional vibration analysis and high frequency analysis. The E1437 module includes input signal conditioning and an 8 MHz anti-alias filter that guarantees that signals outside the analysis bandwidth do not corrupt data samples.

A benefit of a VXI data acquisition system is its ability to trigger all the DAQ boards installed in the mainframe, and also across multiple mainframes, at the same time to provide simultaneous sampling. Besides the capability of recording accelerometer, speed, torque and general voltage measurements such as pressure and strain, the DEMDTB data acquisition system is also capable of recording up to 32 channels of temperature data utilizing an Omega TempScan unit. A National Instrument input/output (I/O) board (VXI-AO-48XDC) is also provided in the VXI mainframe for basic I/O monitoring and control. This high-precision analog source module has 48 voltage (±10.1v) and 48 current outputs (0-20.2ma) for the generation 96 analog signals with 18-bits of resolution. The VXI-AO-48XDC also provides 32 bi-directional TTL compatible digital I/O lines for control and sensing.

The DEMDTB utilizes a second computer whose primary purpose is control and automation of the test bed. The control computer system consists of a Pentium based rack mount computer that utilizes a National Instruments (NI) PCI based data acquisition board (PCI-6025E) for monitoring and control of the diesel test bed operations and auxiliary support systems. The NI card has the capability of simultaneously sampling up to 16 analog channels with a 200Ksamples/sec sample rate. This card also includes 12-bit analog output channels and 32 digital input/output lines for control and sensing signals.

Custom software was developed for both the DAQ and control computers with open systems architecture (OSA) and the Internet in mind. Each of the programs can be setup and controlled remotely via the Internet using a TCP/IP protocol. During testing operations, the control computer will monitor and control the diesel, electric motors, support systems and the VXI data acquisition computer. The DAQ computer will record data and process diagnostic features between snapshots. These diagnostic features will provide warnings and alarms to the operator along with emergency shutdown signals to the control computer. The distributed network system described above is shown in Figure 5.

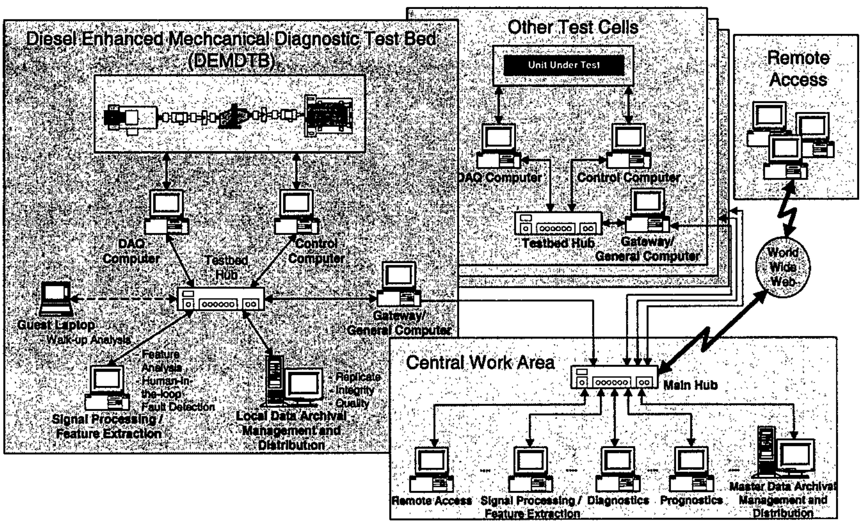


Figure 5 - Global Data Management Network System Architecture

Various computers will be attached locally to the DEMDTB network to process and manage the data generated from the test bed. The DAQ computer will instruct the data archival computer to generate a local mirror image of the collected data and then prompt the processing computer to perform analysis on the latest snapshot of data. A gateway computer on the test bed network will allow remote control via the World Wide Web along with remote data analysis and management.

The DEMDTB as well as several other test cells are centrally supported by the central network system. This provides the capability to conduct data archival/retrieval, signal processing, diagnostic analysis and prognostic analysis from remote locations as well as provide the general public access to the research being conducted through the World Wide Web.

Advanced Diagnostics and Prognostics: Previous diagnostics research has offered insight into the primary failure modes and component failure rates for representative diesel engines. Work has also been conducted to provide measurement parameters as indicators for typical engine faults. Although the state of diesel engine diagnostics has been well developed, there is still no mechanism for predicting the remaining useful life (RUL), which is the ultimate goal of any CBM plan. In an effort to develop the capability to predict the engine component or system RUL, the ARL/Penn State Condition Based Maintenance department proposes to evaluate the use of advanced diagnostic/prognostic techniques. In addition to measuring the standard parameters used for diesel engine diagnostics such as pressure, temperature, flow rate, displacement and vibration, the use of torsional vibration analysis [9] and structural surface intensity [10] will be monitored to evaluate their ability to reliably diagnose and track diesel engine fault conditions. These parameters can be further enhanced to provide a possible prognostic metric by the use of statistical feature extraction [11], which can accentuate

the reaction effect of the measured indication parameter to progressing engine component failure. Feature analysis also lends itself well to the application of pattern recognition and tracking techniques, which are necessary for the implementation of a real time condition monitoring system. Increasing the reliability and effectiveness of diesel engines will require the ability to constantly monitor the engine's operational parameters for the purpose of extracting and processing the useful information that reveals the health condition of the engine and future effectiveness of the prime mover.

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References:

1. Sharpe, R., Jane's Fighting Ships. 102 ed. Directory and Database Publishers Association, 1999.
2. Tank Automotive Research, Development and Engineering Center (TARDEC), **http://www.tacom.army.mil/tardec/engmain.htm**
3. Perakis, A. N. and I. Bahadir, *Reliability Analysis of Great Lakes Marine Diesels: State of the Art and Current Modeling*, Marine Technology, Vol. 27, No.4, pp. 237-249, July 1990.
4. Kawasaki, Y., *The Marine Diesel Engine and its Reliability Problems,* Bulletin of the Marine Engineers Society of Japan, Vol. 8, No. 1, pp. 3-13.
5. Challen, B., Editor, Diesel Engine Reference Book. SAE International: Warrendale, PA, 1998.
6. Hunt, G. A., *Diesel Engine Analysis Review*, ASME ICE Div., Vol. 27-1, pp. 109-117, 1997.
7. Long, B. R. and K. D. Boutin, *Enhancing the Process of Diesel Engine Condition Monitoring,* ASME ICE Div. 1996 Fall Technical Conference, Vol. 27-1, pp. 61-68, 1996.
8. Collacott, R. A., Mechanical Fault Diagnosis and Condition Monitoring. Halstead Press: New York, 1977.
9. Maynard, K. P., et al, *Application of Double Resampling to Shaft Torsional Vibration Measurement for the Detection of Blade Natural Frequencies*, Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, VA, pp. 87-94.
10. Banks, J. and S. Hambric, *Structural Surface Intensity as a Diagnostic Indicator of machinery Condition*; Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, VA, pp. 551-558.
11. McClintic, K., et al, *Residual and Difference Feature Analysis with Transitional Gearbox Data*, Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, VA, pp. 635-645.